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Design of experiments for laser metal deposition in maintenance, repair and overhaul applications

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Modern and expensive parts lead to an increasing demand for maintenance, repair and overhaul (MRO) technologies. Instead of part replacement, MRO technologies are economically advantageous throughout the life cycle. Laser metal deposition as modern MRO technology can be used to repair cracks or protect damaged surfaces with a hard facing layer. It is necessary to adjust weld bead profile to the specific task. For this purpose, Design of Experiment (DoE) has a high potential to decrease experimental effort. In this paper, a full factorial design is used to determine the effect of process parameters on the geometric dimensions of the weld bead. The paper is of interest to engineers working with laser metal deposition as well as DoE methods.

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Keywords: Design of experiments; laser metal deposition; laser powder cladding; repair welding; MRO**1. Motivation / State of the Art**

Many high technology manufacturing companies offer technology intensive products and through-life engineering services. For these expensive products, maintenance, repair and overhaul (MRO) technologies are cost effective throughout the life cycle. Laser metal deposition is increasingly used for these applications.

1.1. Laser metal deposition

Laser metal deposition is a technology to create a metallurgically bonded material deposition on a substrate. The technology is shown in figure 1. A laser beam is used to melt the surface of a specimen. A powdery filler material is injected in the molten pool. After solidification, the filler material forms single weld beads.

The process is characterized by a low heat input, which leads to low distortion and low thermal damage in the base

material. The degree of dilution is below 5 % and a fine microstructure can be achieved. Low metallurgical impact is particularly important for modern materials like high strength steels (e.g. dual-phase or martensitic steel) or nickel-based superalloys, because their microstructure is crucial for their material properties. Because of these advantages, laser metal deposition is increasingly used in MRO applications. Examples are found in the mould and die industry. Laser metal deposition can be used for the repair of sintered tools [1] or with vanadium-carbide tool steel for die repair [2].

Nomenclature

P	laser power	Watt
d	laser spot diameter	mm
v	welding velocity	mm / min
m	powder mass flow	g / min
w	weld bead width	mm
h	weld bead height	mm

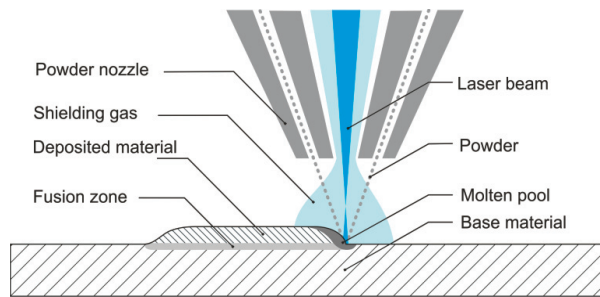


Fig. 1. Laser metal deposition

The state of the art of laser metal deposition is described in [3]. Application as repair technology for stainless steel and titanium alloys is shown in [4].

1.2. Design of experiments

Design of experiments (DoE) is an important tool in engineering. Compared to simplified methods such as the one-factor at a time approach, DoE allows reducing experimental effort. Experimental results are evaluated based on statistical methods and the effects of process parameters on experimental results can be calculated. Different DoE methods have been developed in the past and have been used for laser metal deposition.

For example, a central composite design was used by Sun to determine the effect of process parameters on degree of dilution for titanium alloy [5]. Paul [6] and Lee [7] used a Taguchi design to determine the influence on deposition rate.

Comparative studies between different DoE methods have been done by Youssef [8] for a lathe turning operation.

1.3. Applications

Laser metal deposition can be used in different repair applications with specific requirements regarding weld bead geometry. In order to repair worn surfaces or to produce a hard facing layer, weld beads with a flat and wide geometry are advantageous. They can be deposited next to each other in order to cover a large surface. The repair of damaged volumes, e.g. tip repair for compressor blades, requires high and narrow weld beads. They are deposited on top of each other to rebuild the damaged volume, see figure 2. In order to adjust the welding process for a specific repair task, knowledge about process parameters and their influence on weld bead geometry is necessary.

In addition, this knowledge is needed in order to automate the process. Based on three dimensional scanning to obtain a model of the damaged area, adequate bead geometry needs to be chosen. With statistical methods the corresponding welding parameters can be determined.

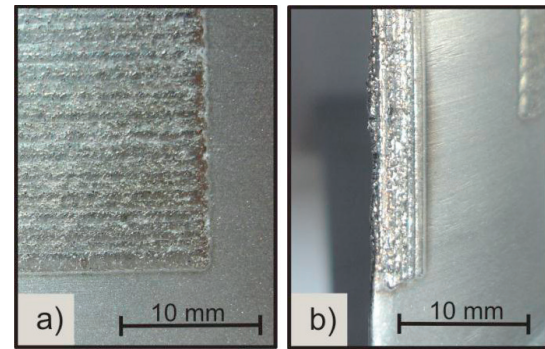


Fig. 2. Different weld bead shapes;

a) surface: flat and wide weld bead b) volume: high and narrow weld bead

2. Experimental

2.1. Materials and experimental procedure

A TRUMPF TruDisk 2.0 kW Yb:Yag laser was used for metal deposition. For all experiments, 4 litre / min Helium 5.0 was used as carrier gas for the powdery filler material, and 10 litre / min Argon 5.0 was used as shielding gas. Nickel based superalloy René 80 was used as filler material with a powder grain size between 45-125 μm . The chemical composition of filler material René 80 is shown in table 1.

Table 1. Chemical composition René 80, manufacturer specification in wt.-%

Cr	Co	Ti	Mo	W	Al	C	B	Ni
14,0	9,4	5,0	4,0	4,0	3,0	0,16	0,02	balance

Single weld beads were deposited using a DoE full factorial design with factor levels according to table 2. All factor levels are combined with each other, resulting in 2^4 combinations. A randomized schedule was used. To improve statistical reliability, each factor combination was used twice in the experiment.

The effect of single factors is analysed by comparing mean responses. Weld bead width and height were measured using tactile measurement device *Hommel nanoscan 855*.

Table 2. Factor levels for DoE

	-1 (min.)	+1 (max)
Laser power P in W	800	1700
Spot diameter d in mm	1,2	1,8
Welding velocity v in mm/min	320	680
Powder mass flow \dot{m} in g/min	5,0	11,0

3. Results and Discussion

3.1. Effects on bead width and height

The different factor combinations result in different weld beads. Bead width was measured in the range of 1.7 mm to 3.0 mm and a height in the range of 0.4 mm to 1.8 mm. So the varied welding parameters have a substantial impact on weld bead geometry.

The effect of welding parameters on bead width and height is shown in figure 3. For bead width, laser power has the biggest effect while powder mass flow has no significant effect in the used parameter range. The bead height is mainly influenced by welding velocity and powder mass flow.

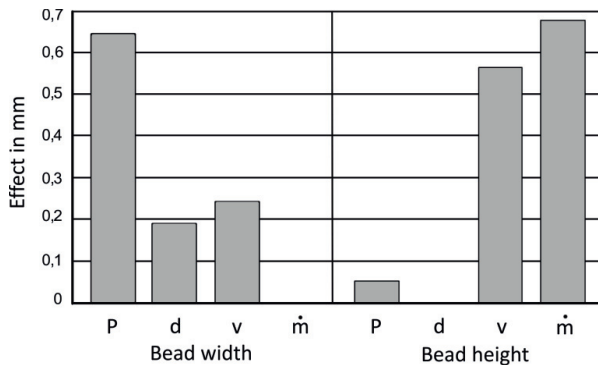


Fig. 3. Effect of welding parameters on bead width and height

The large effects allow to adjust the bead geometry by varying parameters accordingly. Using a linear combination of all effects and their interactions, an expected geometry can be calculated for normalized welding parameters with the following functions:

$$\text{width} = \left(2,32 + \frac{0,64}{2}P + \frac{0,2}{2}d - \frac{0,26}{2}v - \frac{0,14}{2}v\dot{m} \right) \text{ mm} \quad (1)$$

$$\text{height} = \left(0,96 + \frac{0,06}{2}P - \frac{0,57}{2}v + \frac{0,69}{2}\dot{m} - \frac{0,06}{2}Pd - \frac{0,17}{2}v\dot{m} \right) \text{ mm} \quad (2)$$

In function (1) and (2) interactions between the process parameters velocity v and mass flow \dot{m} , and power P and diameter d are shown. Compared to the main factors, the effect of those interactions is relatively small.

3.2. Homoscedasticity

Figure 4 and figure 5 show a comparison between predicted values according to functions (1) and (2) and measurements. The straight line demonstrates the ideal case, where predicted values and measurements are the same. The ideal case is only theoretically possible, when there is no random influence, no measurement inaccuracy and the examined parameters can fully explain every change in weld bead geometry.

Homoscedasticity can be assumed. The distance between measurement and predicted value is not dependent on the value of the measurement.

In figure 5, residuals are smaller than 0.1 mm. The small residuals demonstrate that the model with its predicted values for bead height is in good agreement to the experiments. It is noticeable that the residuals for bead height are grouped together in clusters. Figure 3 shows that bead height is mainly influenced by velocity and powder mass flow. Those factors are used with two values (+1) and (-1) according to table 2, resulting in four possible combinations of their factor values. Those combinations can be seen as clusters in figure 5. High powder mass flow (+1) combined with low velocity (-1) relates to the cluster with highest values. Measurements for low powder mass flow (-1) and high velocity (+1) are in the cluster with lowest bead height. All other combinations are grouped together in the middle cluster. The interaction between velocity and powder mass flow according to function 2 is also visible. A low velocity leads to a larger effect for powder mass flow, therefore a higher increase of bead height when increasing powder mass flow. Consequently, the upper cluster in figure 5 is further away from the middle cluster.

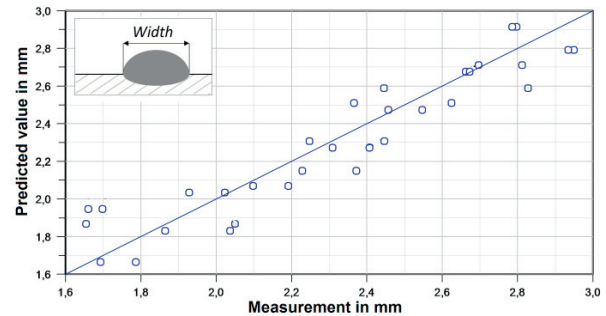


Fig. 4. Predicted values according to (1) and measurement; bead width

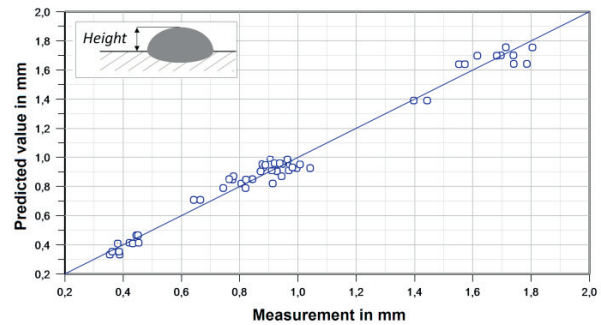


Fig. 5. Predicted values according to (2) and measurement; bead height

3.3. Limitations

The full factorial design requires the experimental use of all possible parameter combinations. This is advantageous in order to analyse all effects and interactions. One limitation of the full factorial design is the size of the design space, because constraints on parameter combinations cannot be included. For example, it would be interesting to extend the design space with higher welding velocity up to 1000 mm/min. But this welding velocity can only be used together with high (+1) laser power. In combination with low (-1) laser power, energy input per unit length would be too low and the welding process would not run. So in the case studied, it is not possible to use a full factorial design with higher welding velocity.

An alternative are computer calculated experimental designs, e.g. D-optimal designs. Those designs are able to exclude parameter combinations which are impossible to run. As a drawback, the design matrix is not orthogonal and confounding among effects and interactions occur.

3.4. Use in MRO applications

In MRO applications, it is necessary to have flexible repair technologies which can be adjusted quickly to the specific repair task. The results of this study can be used to save time in the repair operation. With functions (1) and (2) it is possible to calculate the expected bead geometry and to adjust it to the repair task. Without further experimental effort, process parameters for a wide weld bead can be chosen for surface damages. To increase deposition rate, parameters for a large weld bead width and height can be used. For MRO applications with a small damaged volume, welding parameters leading to a small bead can be chosen accordingly.

It is of further practical relevance, that the main factors in function (1) and (2) with effect on width and height are different. This allows for independent adjustment of the different bead dimensions.

Functions (1) and (2) can be used to adjust the welding process for additional conditions. For example, in some cases a high welding velocity (which generally means short cooling times) is needed for metallurgical reasons. A high velocity provided, all other parameters can be calculated in order to get the required bead geometry.

4. Summary and outlook

Laser metal deposition can be used for modern MRO applications. Based on different applications, the need for knowledge about the effect of process parameters on weld bead geometry is derived. A full factorial design is used to determine the effect of welding parameters on weld bead geometry. A good agreement between the statistical model and experimental results is obtained.

The full factorial design was chosen in order to use all parameter combinations and to analyse their interactions. One limitation of this design is that no constraints can be included in the design space. In future work, computer calculated D-optimal designs with constrained design space can be used. With the drawback of less statistical accuracy, these designs allow to expand the design space, for example with higher welding velocity or smaller spot diameter.

Current research activities concern the automation of laser metal deposition. In a process chain with a three dimensional scanning process, material deposition can be used to rebuild damaged areas. Based on a three dimensional model of the damaged area, welding bead shape has to be chosen correspondingly. Statistical methods offer an important contribution for this process step and therefore for an automated repair process.

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